

Discovery reach of CP violation in neutrino oscillation experiments with standard and non-standard interactions

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Considering Daya Bay experimental value of $\sin \theta_{13}$ we find that for standard interaction of neutrinos with matter the better discovery reach of CP violation is possible in short baseline neutrino oscillation experiment. However, this changes in presence of non-standard interactions (NSIs). For small non-standard interactions (small $\varepsilon_{\alpha\beta}$) long baseline is found to be more suitable, in general, for better discovery reach of CP violation. Even for large value of NSI $\varepsilon_{e\mu}$ long baseline is found to be better. We have also discussed discovery reach of hierarchy and the discovery reach of different NSIs for longer baseline.

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I. INTRODUCTION

Among the various neutrino oscillation parameters the values of two mixing angles θ_{12} and θ_{23} have been provided by experiments with certain accuracy. The magnitude of the mass square differences $|\Delta m_{31}^2|$ and Δm_{21}^2 are also known but the sign of Δm_{31}^2 is still not known i.e. we still do not know exactly if neutrino masses follow normal hierarchy (NH) or inverted hierarchy (IH). Apart from that we still do not know about the CP violating phase δ . Earlier, the third mixing angle $\sin^2 2\theta_{13}$ was also not known accurately except its upper bound but recently the Daya Bay experiment [1] have predicted the value of this parameter with 5σ confidence level. Now the only unknowns in the neutrino mixing matrix - so called PMNS matrix are CP violating phase δ and the hierarchy of neutrino masses.

In this work we consider neutrino superbeam (which mainly contains ν_μ and $\bar{\nu}_\mu$) coming from CERN travelling a baseline length of 2300 Km reaches Pyhäsalmi (Finland) where a Liquid Argon detector is placed. We also consider another baseline of 130 Km with a superbeam source at CERN and Water Cherenkov detector placed at Fréjus (France). We do a comparative study in the discovery potentials of the CP violating phase δ for these two baselines in presence of both standard and non-standard interactions.

This paper is organised as follows: In section II we discuss how the probability of oscillation for $\nu_\mu \rightarrow \nu_e$ for short and long baseline differ when NSIs are taken into account. In section III we discuss the experimental setup and assumptions in doing the numerical analysis using GLOBES [2]. In section IV we discuss the discovery reaches of CP violation, hierarchy and NSIs. Finally in section V we conclude with remarks on the prospects of short and long baselines neutrino oscillation experiments.

II. NEUTRINO OSCILLATION PROBABILITIES WITH NSI

In addition to the Standard Model (SM) Lagrangian density we consider the following non-standard fermion-neutrino interaction in matter defined by the Lagrangian:

$$\mathcal{L}_{NSI}^M = -2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{fP} [\bar{f}\gamma_\mu P f][\bar{\nu}_\beta \gamma^\mu L \nu_\alpha] \quad (1)$$

where $P \in (L, R)$, $L = \frac{(1-\gamma^5)}{2}$, $R = \frac{(1+\gamma^5)}{2}$, $f = e, u, d$ and $\varepsilon_{\alpha\beta}^{fP}$ is the deviation from SM interactions and can be called as the non-standard interactions(NSIs). A bound can be set to these NSI parameters [3, 4] which are dependent on specific models [5, 6] or are also model independent [7]. These NSI parameters can be reduced to the effective parameters and can be written as:

$$\varepsilon_{\alpha\beta} = \sum_{f,P} \varepsilon_{\alpha\beta}^{fP} \frac{n_f}{n_e} \quad (2)$$

where n_f is the fermion number density and n_e is the electron number density. These NSIs play significant role in the context of neutrino oscillation experiments and modify the interaction of neutrinos with matter and thus change the oscillation probability of different flavor of neutrinos. The NSIs could be present at the source of neutrinos, during the propagation of neutrinos and also during detection of neutrinos [8]. The NSI effects are expected to be smaller at the source and detector due to their stringent constraints [7]. We shall consider the NSI effect during the propagation of neutrinos only and in section IV in presenting results of

our numerical analysis we shall consider the model independent allowed range of real values of different NSIs as mentioned in reference [7] for earth like matter.

In vacuum, flavor eigenstates ν_α may be related to mass eigenstates of neutrinos ν_i as

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle; \quad i = 1, 2, 3, \quad (3)$$

where U is PMNS matrix [9] which depends on three mixing angles θ_{12} , θ_{23} and θ_{13} and one CP violating phase δ . Although two more Majorana phases could be present in U but are not relevant for neutrino oscillation experiments. The Hamiltonian due to standard (H_{SM}) and non-standard interactions (H_{NSI}) of neutrinos interacting with matter during propagation can be written in the flavor basis as:

$$H = H_{SM} + H_{NSI} \quad (4)$$

where

$$H_{SM} = \frac{\Delta m_{31}^2}{2E} \left[U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \right], \quad (5)$$

$$H_{NSI} = A \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix} \quad (6)$$

In equations (5) and (6)

$$A = \frac{2E\sqrt{2}G_F n_e}{\Delta m_{31}^2}; \quad \alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}; \quad \Delta m_{ij}^2 = m_i^2 - m_j^2 \quad (7)$$

where m_i is the mass of the i -th neutrino and A is considered due to the interaction of neutrinos with matter in SM, G_F is the Fermi constant and n_e is the electron number density of matter. ε_{ee} , $\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$, $\varepsilon_{\mu\mu}$, $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau}$ are considered due to the non-standard interaction (NSIs) of neutrinos with matter. In equation (6), $(*)$ denotes complex conjugation. In general, the NSIs - $\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$ and $\varepsilon_{\mu\tau}$ could be complex. However, in our numerical analysis we have considered those to be real.

For understanding qualitatively which baseline is suitable for discovery reach of CP violation and hierarchy in presence of standard and non-standard interactions we present below the oscillation probability $P_{\nu_\mu \rightarrow \nu_e}$ for both short and long baseline. $\nu_\mu \rightarrow \nu_e$ oscillation channel is particularly sensitive to CP violation. In our numerical analysis however, we have considered other channels also like $\nu_\mu \rightarrow \nu_\mu$. To get these expressions of probability we have followed the perturbation method adopted in references [8, 10–12]. At first, we shall present the oscillation probability upto order α^2 as the CP violating phase δ appears at this order for only SM interactions as well as for small NSI of the order of α . For short baseline of 130 Km keeping the matter effect parameter A at the $\mathcal{O}(\alpha)$ and considering NSI parameters $\varepsilon_{\alpha\beta}$ of the order of α one obtains

$$\begin{aligned}
P_{\nu_\mu \rightarrow \nu_e} = & \frac{L^2 \alpha^2 \Delta m_{31}^4 \cos[\theta_{23}]^2 \sin[2\theta_{12}]^2}{16E^2} + \sin\left[\frac{L\Delta m_{31}^2}{4E}\right] \left(-2AL\Delta m_{31}^2 \cos\left[\frac{L\Delta m_{31}^2}{4E}\right] \right. \\
& + 2E(1+4A+\cos[2\theta_{13}]) \sin\left[\frac{L\Delta m_{31}^2}{4E}\right] \left. \frac{\sin[\theta_{13}]^2 \sin[\theta_{23}]^2}{E} \right. \\
& + \frac{L\alpha\Delta m_{31}^2 \sin[\theta_{13}] \sin[\theta_{23}]}{E} \left(\cos\left[\delta + \frac{L\Delta m_{31}^2}{4E}\right] \cos[\theta_{23}] \sin\left[\frac{L\Delta m_{31}^2}{4E}\right] \sin[2\theta_{12}] \right. \\
& \left. \left. - \sin\left[\frac{L\Delta m_{31}^2}{2E}\right] \sin[\theta_{12}]^2 \sin[\theta_{13}] \sin[\theta_{23}] \right) \right) \quad (8)
\end{aligned}$$

For 2300 Km the matter effect is large. Keeping A in the leading order of perturbation and considering NSI parameters $\varepsilon_{\alpha\beta}$ of the order of α one obtains

$$\begin{aligned}
P_{\nu_\mu \rightarrow \nu_e} = & \frac{\alpha^2 \cos^2[\theta_{23}] \sin^2\left[\frac{AL\Delta m_{31}^2}{4E}\right] \sin^2[2\theta_{12}]}{A^2} \\
& + \frac{a_6 \left(8E \sin^2\left[\frac{(-1+A)L\Delta m_{31}^2}{4E}\right] - (-1+A)L\Delta m_{31}^2 \sin\left[\frac{(-1+A)L\Delta m_{31}^2}{2E}\right] \right) \sin^2[\theta_{13}] \sin^2[\theta_{23}]}{(-1+A)^3 E} \\
& + \frac{a_1 \left(-8E \sin^2\left[\frac{(-1+A)L\Delta m_{31}^2}{4E}\right] + (-1+A)L\Delta m_{31}^2 \sin\left[\frac{(-1+A)L\Delta m_{31}^2}{2E}\right] \right) \sin^2[\theta_{13}] \sin^2[\theta_{23}]}{(-1+A)^3 E} \\
& + \frac{\sin\left[\frac{(-1+A)L\Delta m_{31}^2}{4E}\right] \sin^2[\theta_{13}] \sin^2[\theta_{23}]}{(-1+A)^4 E} (2E(1+(-6+A)A \\
& + (1+A)^2 \cos[2\theta_{13}]) \sin\left[\frac{(-1+A)L\Delta m_{31}^2}{4E}\right] \\
& + 4(-1+A)AL\Delta m_{31}^2 \cos\left[\frac{(-1+A)L\Delta m_{31}^2}{4E}\right] \sin^2[\theta_{13}]) \\
& + \frac{4a_2 \cos[\theta_{23}]}{(-1+A)A^2} \sin\left[\frac{AL\Delta m_{31}^2}{4E}\right] \left((-1+A) \cos[\theta_{23}] \sin\left[\frac{AL\Delta m_{31}^2}{4E}\right] (a_2 + \alpha \cos[\phi_{a_2}] \sin[2\theta_{12}]) \right. \\
& + 2A \cos\left[\delta + \frac{L\Delta m_{31}^2}{4E} + \phi_{a_2}\right] \sin\left[\frac{(-1+A)L\Delta m_{31}^2}{4E}\right] \sin[\theta_{13}] \sin[\theta_{23}]) \\
& + \frac{\alpha \sin[\theta_{12}] \sin[\theta_{13}] \sin[\theta_{23}]}{(-1+A)^3 AE} \left(8(-1+A)^2 E \cos\left[\delta + \frac{L\Delta m_{31}^2}{4E}\right] \cos[\theta_{12}] \cos[\theta_{23}] \times \right. \\
& \sin\left[\frac{(-1+A)L\Delta m_{31}^2}{4E}\right] \sin\left[\frac{AL\Delta m_{31}^2}{4E}\right] + A \left(-8AE \sin^2\left[\frac{(-1+A)L\Delta m_{31}^2}{4E}\right] \right. \\
& + (-1+A)L\Delta m_{31}^2 \sin\left[\frac{(-1+A)L\Delta m_{31}^2}{2E}\right] \left. \right) \sin[\theta_{12}] \sin[\theta_{13}] \sin[\theta_{23}]) \\
& - \frac{4a_2 a_3 \sin[2\theta_{23}]}{(-1+A)A} \cos\left[\frac{L\Delta m_{31}^2}{4E} + E - \phi_{a_3}\right] \sin\left[\frac{(1-A)L\Delta m_{31}^2}{4E}\right] \sin\left[\frac{AL\Delta m_{31}^2}{4E}\right] \\
& + \frac{4a_3 \sin\left[\frac{(-1+A)L\Delta m_{31}^2}{4E}\right] \sin[\theta_{23}]}{(-1+A)^2 A} \left((-1+A)\alpha \cos[\theta_{23}] \cos\left[\frac{L\Delta m_{31}^2}{4E} - \phi_{a_3}\right] \times \right.
\end{aligned}$$

$$\begin{aligned}
& \sin \left[\frac{AL\Delta m_{31}^2}{4E} \right] \sin[2\theta_{12}] + A \sin \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] \sin[\theta_{23}](a_3 + 2 \cos[\delta + \phi_{a_3}] \sin[\theta_{13}]) \\
& + \frac{a_5 \sin \left[\frac{(-1+A)L\Delta m_{31}^2}{4E} \right] \sin^2[\theta_{13}]}{(-1+A)^2 A} \sin[2\theta_{23}] \left(-4A \cos \left[\frac{AL\Delta m_{31}^2}{4E} \right] \cos[\phi_{a_5}] \sin \left[\frac{L\Delta m_{31}^2}{4E} \right] \right. \\
& \left. + 4 \sin \left[\frac{AL\Delta m_{31}^2}{4E} \right] \left(\cos \left[\frac{L\Delta m_{31}^2}{4E} \right] \cos[\phi_{a_5}] - (-1+A) \sin \left[\frac{L\Delta m_{31}^2}{4E} \right] \sin[\phi_{a_5}] \right) \right) \quad (9)
\end{aligned}$$

where

$$\begin{aligned}
a_1 &= A\varepsilon_{ee} \\
a_2 &= \frac{A\sqrt{|\varepsilon_{e\mu}|^2 + |\varepsilon_{e\tau}|^2 + (|\varepsilon_{e\mu}|^2 - |\varepsilon_{e\tau}|^2) \cos 2\theta_{23} - 2|\varepsilon_{e\mu}||\varepsilon_{e\tau}| \cos[\phi_{e\mu} - \phi_{e\tau}] \sin 2\theta_{23}}}{\sqrt{2}} \\
a_3 &= \frac{A\sqrt{|\varepsilon_{e\mu}|^2 + |\varepsilon_{e\tau}|^2 + (-|\varepsilon_{e\mu}|^2 + |\varepsilon_{e\tau}|^2) \cos 2\theta_{23} + 2|\varepsilon_{e\mu}||\varepsilon_{e\tau}| \cos[\phi_{e\mu} - \phi_{e\tau}] \sin 2\theta_{23}}}{\sqrt{2}} \\
a_5 &= A \left(|\varepsilon_{\mu\tau}|^2 \cos^2 2\theta_{23} \cos^2 \phi_{\mu\tau} + (|\varepsilon_{\mu\mu}| - |\varepsilon_{\tau\tau}|)^2 \cos^2 \theta_{23} \sin^2 \theta_{23} + \frac{1}{2} |\varepsilon_{\mu\tau}| ((|\varepsilon_{\mu\mu}| - |\varepsilon_{\tau\tau}|) \cos \phi_{\mu\tau} \sin 4\theta_{23} \right. \\
& \left. + 2|\varepsilon_{\mu\tau}| \sin^2 \phi_{\mu\tau}) \right)^{1/2} \\
a_6 &= A (|\varepsilon_{\tau\tau}| \cos^2 \theta_{23} + |\varepsilon_{\mu\mu}| \sin^2 \theta_{23} + |\varepsilon_{\mu\tau}| \cos \phi_{\mu\tau} \sin 2\theta_{23}) \\
\phi_{a_2} &= \tan^{-1} \left[\frac{|\varepsilon_{e\mu}| \cos \theta_{23} \sin \phi_{e\mu} - |\varepsilon_{e\tau}| \sin \theta_{23} \sin \phi_{e\tau}}{|\varepsilon_{e\mu}| \cos \theta_{23} \cos \phi_{e\mu} - |\varepsilon_{e\tau}| \cos \phi_{e\tau} \sin \theta_{23}} \right] \\
\phi_{a_3} &= \tan^{-1} \left[\frac{|\varepsilon_{e\mu}| \sin \theta_{23} \sin \phi_{e\mu} + |\varepsilon_{e\tau}| \cos \theta_{23} \sin \phi_{e\tau}}{|\varepsilon_{e\tau}| \cos \theta_{23} \cos \phi_{e\tau} + |\varepsilon_{e\mu}| \cos \phi_{e\mu} \sin \theta_{23}} \right] \\
\phi_{a_5} &= \tan^{-1} \left[\frac{|\varepsilon_{\mu\tau}| \sin[\phi_{\mu\tau}]}{|\varepsilon_{\mu\tau}| \cos 2\theta_{23} \cos \phi_{\mu\tau} + (|\varepsilon_{\mu\mu}| - |\varepsilon_{\tau\tau}|) \cos \theta_{23} \sin \theta_{23}} \right] \quad (10)
\end{aligned}$$

For CP violation there is difference of probability in the neutrino oscillation and probability of antineutrino oscillation. One can relate the oscillation probabilities for antineutrinos to those probabilities given for neutrinos above by the following relation:

$$P_{\bar{\alpha}\bar{\beta}} = P_{\alpha\beta}(\delta_{CP} \rightarrow -\delta_{CP}, A \rightarrow -A). \quad (11)$$

In addition, we also have to replace $\varepsilon_{\alpha\beta}$ with their complex conjugates, in order to deduce the oscillation probability for the antineutrino, if one considers non-standard interaction during propagation.

To estimate the order of magnitude of different terms in the above two oscillation probabilities we shall consider $A \sim \alpha$ for short baseline and $A \sim 0.5$ for longer baseline and following Daya Bay result we shall consider $\sin \theta_{13} \sim \sqrt{\alpha}$. For only SM interactions, (i.e $\varepsilon_{\alpha\beta} \rightarrow 0$) in above expressions of oscillation probabilities one finds that for both short and long baseline the δ dependence occurs at order of $\alpha^{3/2}$. This order of dependence with δ remains same in the difference of neutrino oscillation probabilities and antineutrino oscillation probabilities (represented by ΔP later). However, the δ independent part in ΔP (which could mimic CP violation) for short baseline is at order α^2 but for long baseline this is at order α . This happens due to matter effect through A for SM as can be seen from above expressions. For this reason the discovery reach of CP violation is better in short baseline than that in long baseline. However, when

NSIs are also taken into account one can see that for longer baseline further δ dependence in ΔP could occur at the order of $\alpha^{3/2}$ through a_2 and a_3 containing terms in (9) for NSIs of the order of α . We have checked that for slightly higher NSIs of the order of $\sqrt{\alpha}$ using perturbation method the same δ dependent terms in ΔP appears with a_2 and a_3 in the oscillation probability for long baseline as given in (9) and this slightly higher NSI makes these terms at the order of α which could compete with the δ independent part (which could mimic CP violation) in ΔP for long baseline as that is also at the order of α . This improvement of δ dependent part over independent part for long baseline does not happen for short baseline. First of all for NSI of the order of α oscillation probability in (8) for short baseline is independent of NSIs. Even for slightly higher NSIs of order $\sqrt{\alpha}$ we have checked although NSIs like a_2 and a_3 enter into the only δ dependent part of ΔP for short baseline but that is at the order of α^2 . So not much improvement in the discovery reach of CP violation is expected for short baseline for NSIs which are present in a_2 and a_3 . So presence of slightly higher NSIs of order $\sqrt{\alpha}$ present in a_2 and a_3 improves the discovery reach of CP violation for longer baseline in comparison to the short baseline. As a_2 and a_3 contains NSIs like $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ it is expected that in presence of these NSIs the long baseline could provide a better discovery reach for CP violation.

For hierarchy discovery the difference in the oscillation probabilities due to two different hierarchies matters. If we change hierarchy then in above oscillation probabilities the following transformations are to be considered:

$$\Delta m_{31}^2 \rightarrow -\Delta m_{31}^2 ; A \rightarrow -A ; \alpha \rightarrow -\alpha$$

For SM only the above differences of oscillation probabilities between two different hierarchies (ΔP_H) for longer baseline is of the order α due to matter interaction through A . However, for shorter baseline the ΔP_H is of the order $\alpha^{3/2}$. So longer baseline is more suitable for discovery of hierarchy. This remains unaltered even after including NSIs.

III. ANALYSIS AND EXPERIMENTAL SETUP

In this work for the numerical simulation we consider two set-ups: (a) A Superbeam setup which originates in CERN and reaches a 100 kt Liquid Argon detector placed at a distance of 2300 Km at Pyhäsalmi (Finland) (b) A Superbeam setup originating in CERN and reaching a 500 Kt Water Cherenkov detector placed at a distance of 130 Km at Fréjus (France).

We consider a flux with mean neutrino energy around 5 GeV and 3×10^{21} protons on target per year. We consider the same flux as in [13]. For set-up(a) we consider a power of 0.8 MW per year. In doing the analysis we consider a signal efficiency of 90% in both the appearance and disappearance channels. As backgrounds we consider a 0.5% neutral current events, 1% of ν_μ misidentified and the complete intrinsic contamination of the beam. The background rejection efficiencies were assumed to be constant over the energy window of 0.5 to 10 GeV. The calibration error has been considered to be 2% for ν_μ disappearance channel and 0.01% for ν_e appearance channel. The Gaussian energy resolution is considered to be 150 MeV for electrons and positrons and $0.2\sqrt{E}$ for muons. The correlation between the visible energy of background NC events and the neutrino energy is implemented by migration matrices which has been provided by L. Whitehead [14].

In the case of set-up(b) we have considered a beam intensity of 4 MW and a systematics on signal and background as 2% based on ref[15]. A neutrino energy window of 0.5 to 10 GeV has been considered for both

the set-ups and both ν and $\bar{\nu}$ beams have been used simultaneously for a time period of 5 yrs for neutrino and 5 yrs for antineutrino in case of set up (a) 2300 km and 2 yrs for neutrino and 8 yrs for antineutrino in case of set up (b) 130 km.

Following ref [13] we consider the true values of the neutrino oscillation parameters as $|\Delta m_{31}^2| = 2.45 \times 10^{-3} \text{ eV}^2$, $\Delta m_{21}^2 = 7.64 \times 10^{-5} \text{ eV}^2$, $\theta_{13} = 9^\circ$, $\theta_{12} = 34.2^\circ$ and $\theta_{23} = 45^\circ$. Also in calculating the priors we consider an error of 3% on θ_{12} , 0.005 on $\sin^2 2\theta_{13}$, 8% on θ_{23} , 4% on $|\Delta m_{31}^2|$ and 2.5% on Δm_{21}^2 . Also we consider an error of 2% on matter density and a systematic uncertainties of 5 and 10% on signal and background channels. In doing the whole analysis we have used GLoBES software [2]. In this work we have done a comparative study of the two set-ups (a) and (b) in finding the discovery reach of the CP violating phase δ depending on different NSI parameters and the hierarchies. For the longer baseline we have also discussed about discovery reach of hierarchy and NSI.

IV. RESULTS

A. Discovery of CP violation

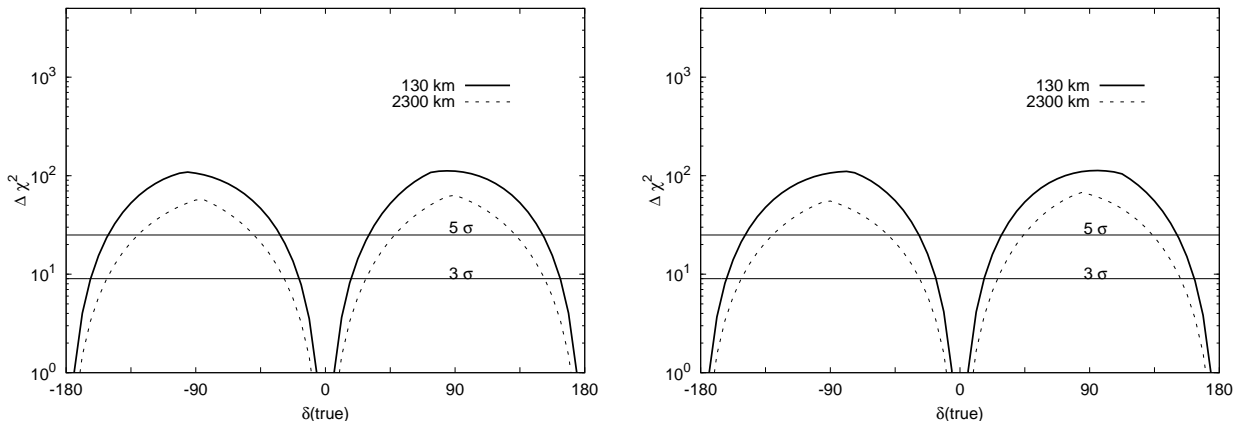


FIG. 1: CP violating phase δ discovery for two different baselines 130 Km and 2300 Km. The right hand panel is for IH and the left hand panel is for NH .

In figure 1 we have shown the discovery reach of CP violation for SM interactions of neutrinos with matter. For 130 Km baseline the CP violation could be discovered over about 67% of the possible δ values for normal hierarchy and this is about 68% for inverted hierarchy whereas for 2300 Km baseline these values are about 46% and 47% respectively. The discovery reach for longer baseline of 2300 Km was shown earlier by Coloma *et al* [13]. So with only SM the short baseline like 130 Km seems to be better for good discovery reach of CP violation. However, this could change depending on the type of NSIs taken into account as discussed below.

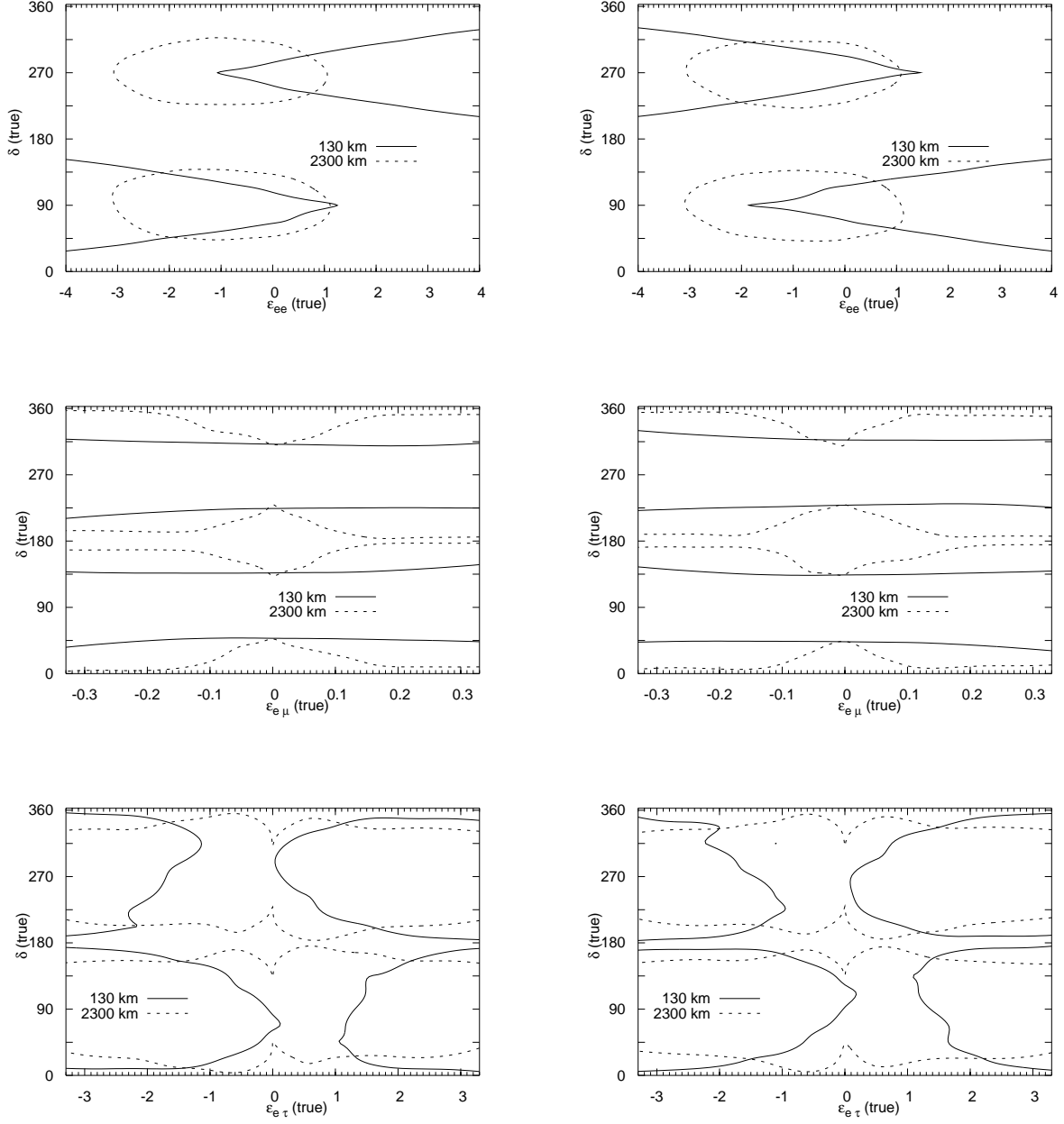


FIG. 2: CP violating phase δ discovery for two different baselines 130 Km and 2300 Km at 5σ considering NSIs ε_{ee} , $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$. The right hand panel is for IH and the left hand panel is for NH .

In figure 2 we have compared the discovery reach of CP violation for 130 Km baseline and 2300 Km baseline in presence of NSIs like ε_{ee} , $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$. For ε_{ee} in the range of about - 2.5 to 0.5 the 2300 Km baseline is found to be better for the discovery reach which could be possible for about 49 % of the possible

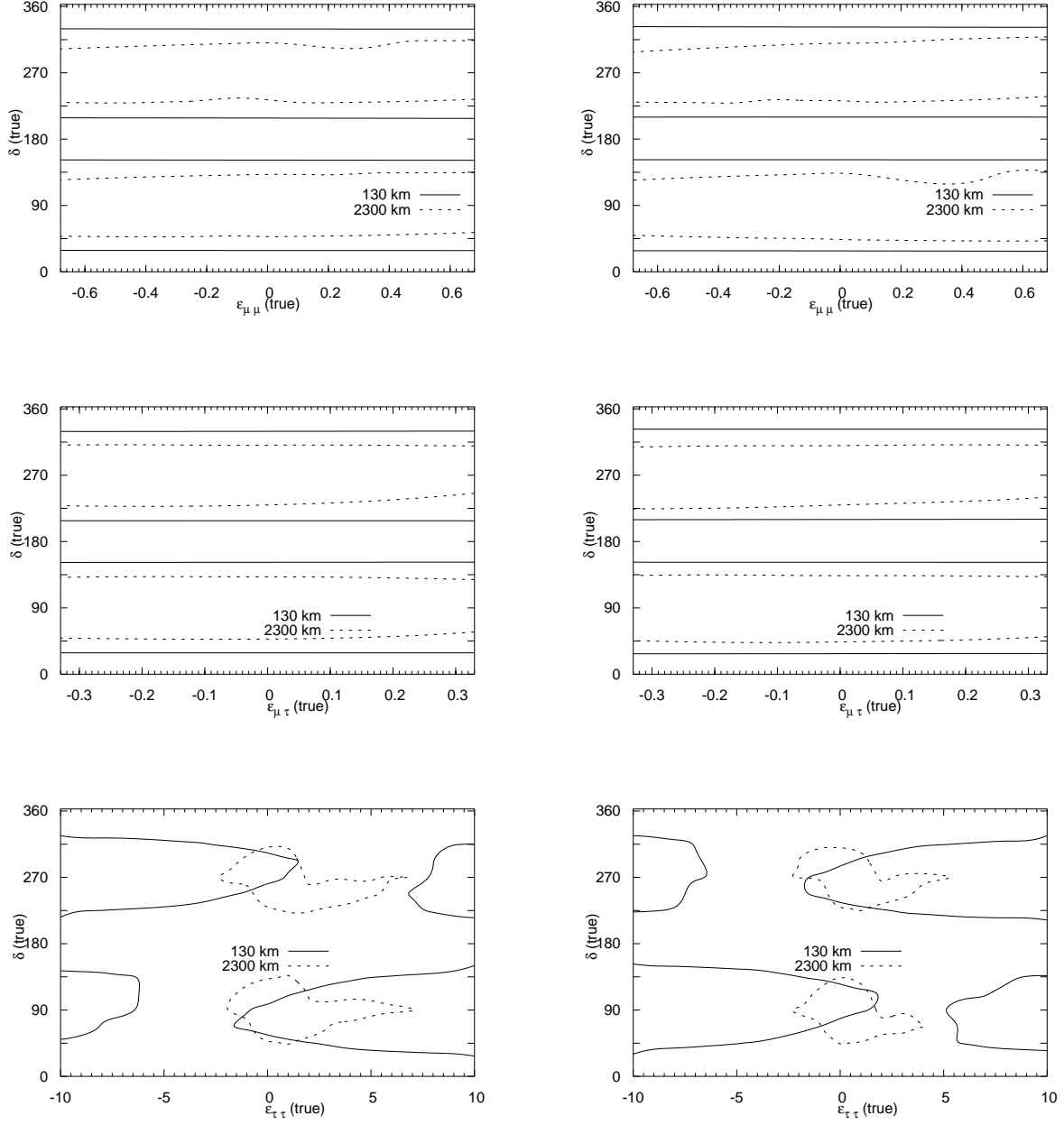


FIG. 3: CP violating phase δ discovery for two different baselines 130 Km and 2300 Km at 5σ considering NSIs $\varepsilon_{\mu\mu}$, $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau}$. The right hand panel is for IH and the left hand panel is for NH .

δ values whereas 130 Km is not so good in this range of NSI ε_{ee} . For somewhat larger NSI around 4 or -4 the short baseline of 130 Km is found to be better for discovery reach which could be possible for about 36% of the possible δ values. It is interesting to note that for NSI - $\varepsilon_{e\mu}$ - the discovery reach is consistently better for 2300 Km than that for 130 Km and could be discovered over 90% of the allowed δ values. For $\varepsilon_{e\tau}$

in 2300 Km CP violation could be discovered over about 70% of the δ values over the entire allowed region of $\varepsilon_{e\tau}$. 130 Km baseline is found to be better for very high $\varepsilon_{e\tau}$ values around 3 and -3 only.

In figure 3 we have compared the discovery reach of CP violation for 130 Km baseline and 2300 Km baseline in presence of NSIs like $\varepsilon_{\mu\mu}$, $\varepsilon_{\mu\tau}$ and $\varepsilon_{e\tau}$. For particularly $\varepsilon_{\mu\mu}$ and $\varepsilon_{\mu\tau}$, 130 Km baseline is found to be better for CP discovery which could be possible over 70 % of the δ values for both the hierarchies throughout the entire allowed region of these NSIs. This is about 43 % for 2300 Km baseline. For $\varepsilon_{\tau\tau}$ in 2300 Km baseline the discovery reach of CP violation could be possible over 50 % of δ values for small NSIs. For 130 Km for large NSIs only good discovery reach of about 61% could be possible. So it is found that except $\varepsilon_{\mu\mu}$ and $\varepsilon_{\mu\tau}$ for other NSIs for their small values the discovery reach for CP violation is better for longer baseline than the shorter baseline.

B. Discovery of hierarchy

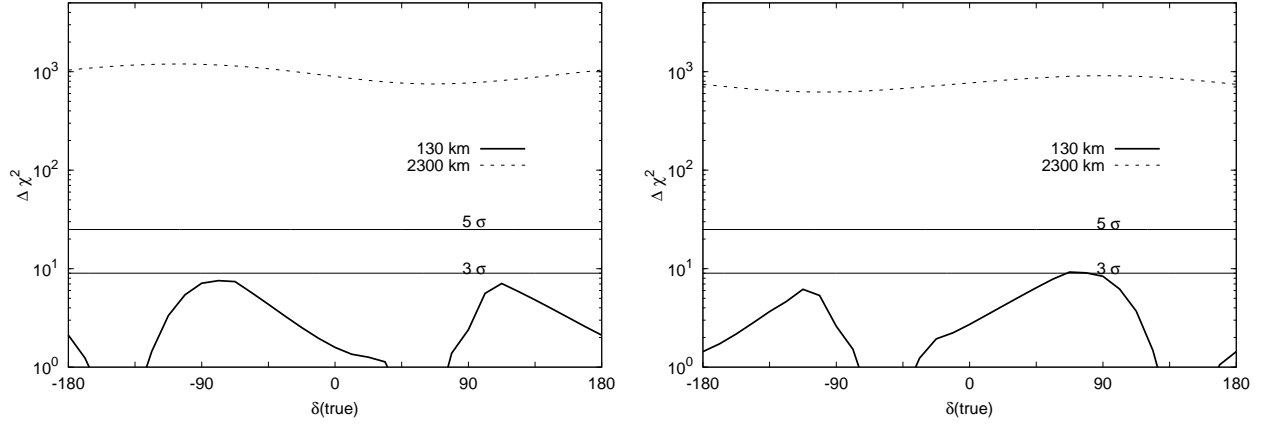


FIG. 4: Discovery reach of hierarchy for two different baselines 130 Km and 2300 Km for SM interactions only. The right hand panel is for IH and the left hand panel is for NH .

In figure 4 it is seen that with only SM interactions the discovery reach of hierarchy could be possible at above 5σ confidence level for 2300 Km baseline. It was shown earlier by Coloma *et al* [13]. The 130 Km baseline is found to be not so suitable for hierarchy as the discovery could be possible at only below 3σ .

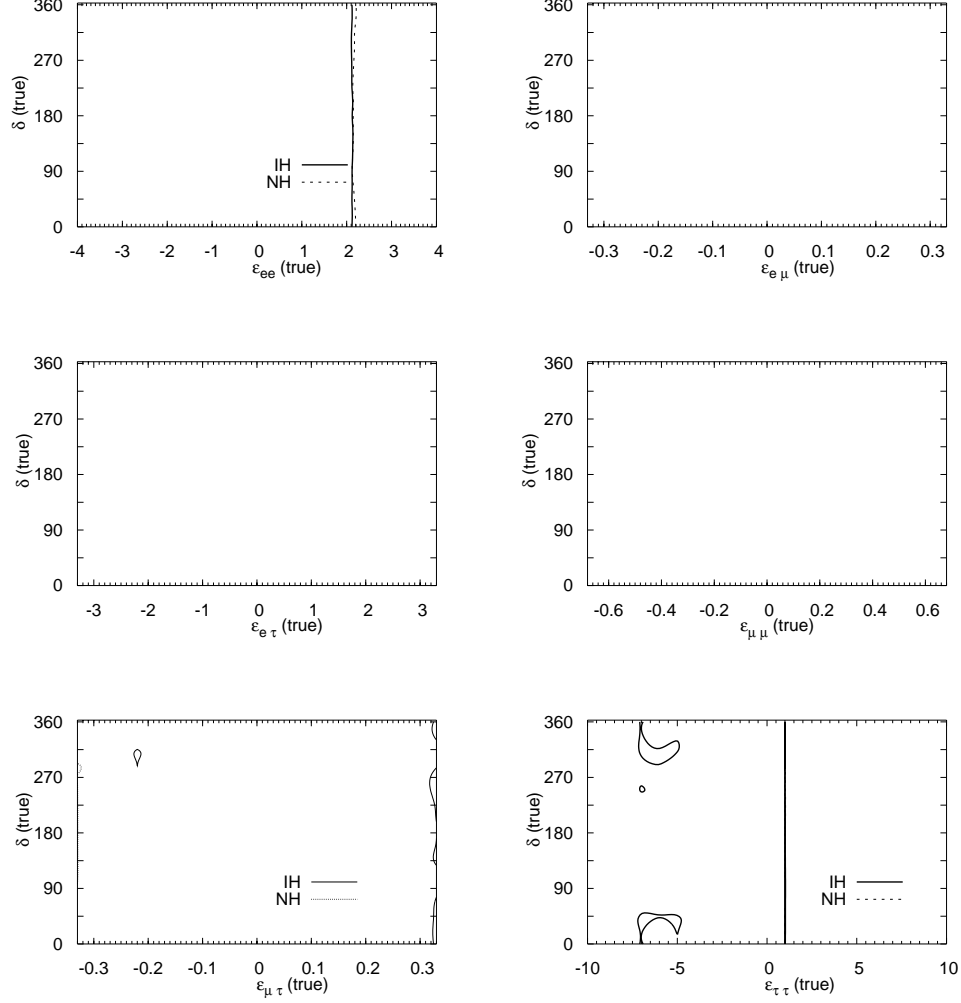


FIG. 5: Discovery reach of hierarchy with NSIs for a baseline of 2300 Km at 3σ .

In figure 5 the discovery reach of hierarchy is shown in the δ NSI plane. Although for entire negative allowed values of ε_{ee} hierarchy could be discovered at 3σ confidence level but for positive values it could be possible for lesser than 2. The discovery reach is possible for the entire allowed region of NSIs particularly for $\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$ and $\varepsilon_{\mu\mu}$. For other NSIs like $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau}$ discovery is possible for almost entire allowed region except few δ and NSI values found in small enclosed areas. For $\varepsilon_{\tau\tau}$ near to about 1 the discovery is difficult.

C. Discovery of NSI

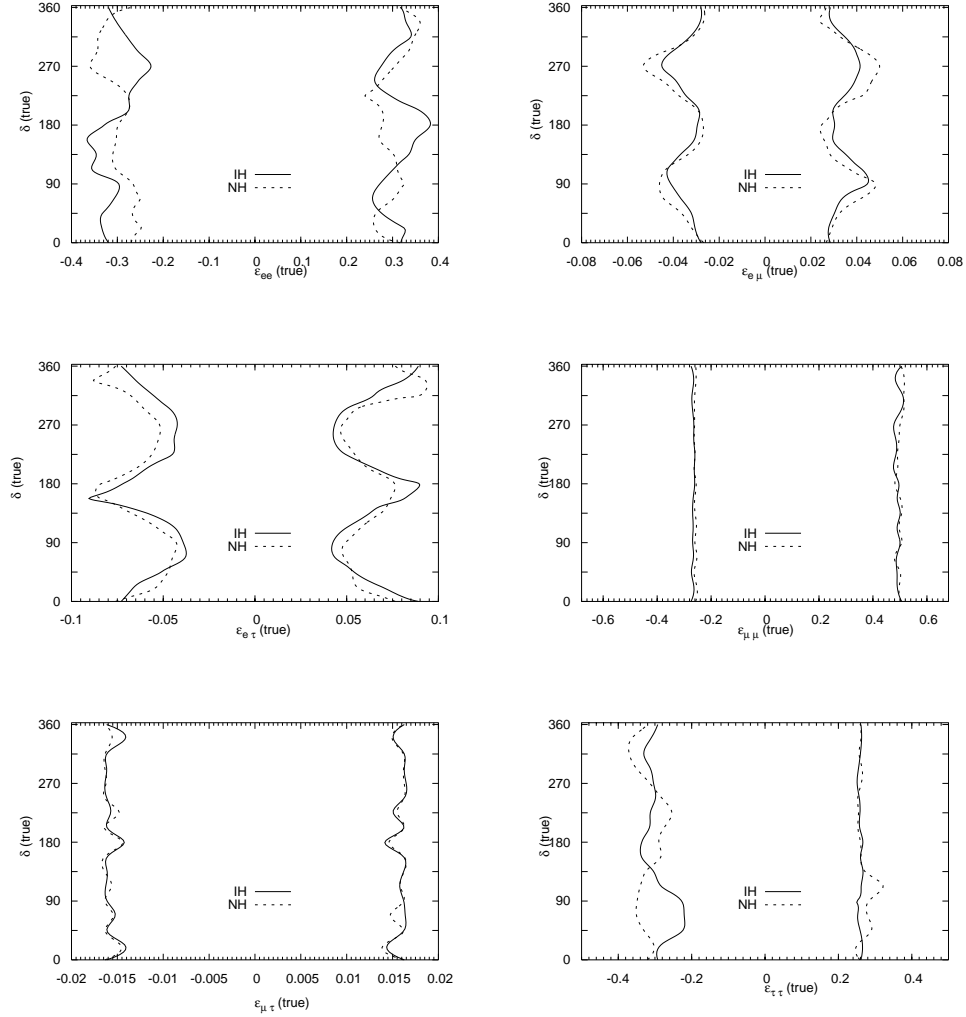


FIG. 6: Discovery reach of NSIs for both the hierarchies for a baseline of 2300 Km at 5σ .

In figure(6) we have shown the discovery reach of different NSIs with δ for both the hierarchies at 5σ confidence level. The NSI discovery reach in the figures are the area bounded by the solid (IH) and dotted (NH) lines for set-up(a) i.e. baseline is 2300 km. However, for set-up(b) i.e. baseline 130 Km (not shown in figure) we are not able to obtain any statistically significant bound on the NSIs in the total allowed range of NSIs. From the figure the range (after approximately averaging for different delta values and also for different hierarchies) over which the different NSIs could be discovered for set-up (a) are given as $-0.32 < \varepsilon_{ee} < 0.32$, $-0.038 < \varepsilon_{e\mu} < 0.036$, $-0.07 < \varepsilon_{e\tau} < 0.075$, $-0.26 < \varepsilon_{\mu\mu} < 0.5$, $-0.016 < \varepsilon_{\mu\tau} < 0.016$ and $-0.3 < \varepsilon_{\tau\tau} < 0.26$.

V. CONCLUSION

In this work we have considered two experimental set-ups - one with a baseline of 2300 Km directed towards a 100 Kt Liquid argon detector and the other with a baseline of 130 Km directed towards a 500 Kt Water Cherenkov detector. Considering the recently obtained value of $\sin\theta_{13}$ from Daya Bay experiment it is found that in presence of only SM interactions the discovery reach of CP violation is better for short baseline like 130 Km than long baseline like 2300 Km. In presence of NSIs $\varepsilon_{\mu\mu}$ and $\varepsilon_{\mu\tau}$ for their entire allowed region the short baseline is found to be more suitable for discovery of CP violation. However, for $\varepsilon_{e\mu}$ over its entire allowed region and also for $\varepsilon_{e\tau}$ over significant part of the allowed region in the δ NSI plane the longer baseline is found to be better. For other NSIs in general for smaller values the longer baseline is better whereas for larger NSI values the shorter baseline is found to be better. In presence of only SM interactions the discovery reach of hierarchy is far superior for longer baseline than that for short baseline. In presence of NSI in long baseline we find that the discovery reach of hierarchy is possible for the entire allowed region of NSIs particularly for $\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$ and $\varepsilon_{\mu\mu}$. However, for allowed region of $\varepsilon_{ee} < 2$ only it is possible to find the good discovery reach at 3σ . For other NSIs like $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau}$ discovery is possible for almost entire allowed region except for few δ and NSI values. The discovery reach of various NSIs are possible in the longer baseline for NSI values greater than the order of α .

The good discovery reach of CP violation crucially depends on the relative contribution of the δ dependent terms in the probability with respect to the δ independent part as discussed in section II. In the longer baseline the NSIs $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ is coupled with δ in the oscillation probability and as such increases the δ dependent contribution and provides the possibility of good discovery reach of CP violation. This does not happen for very large NSI values and the shorter baseline is found to be better for CP violation discovery. One may note that the expression of oscillation probability which we have presented in section II are not valid for such high NSI values. Considering the possibility of the presence of NSIs in nature it seems both short and long baseline should be considered particularly for discovery of CP violation in the leptonic sector through neutrino oscillation experiment.

Acknowledgment: AD thanks Council of Scientific and Industrial Research, India for financial support through Senior Research Fellowship (EMR No. 09/093(0132)/2010-EMR-I) and ZR thanks University Grants Commission, Govt. of India for providing research fellowships. We thank L. Whitehead for helpful communication.

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